Storage ring proton EDM experiment at $10^{-29}\ e \cdot \mathrm{cm}$

On Kim

on behalf of the srEDM collaboration

Based on Snowmass WP arXiv:2205.00830 and
Zhanibek Omarov *et al.*, PRD **105**, 032001 (2022)

2022 July 22nd

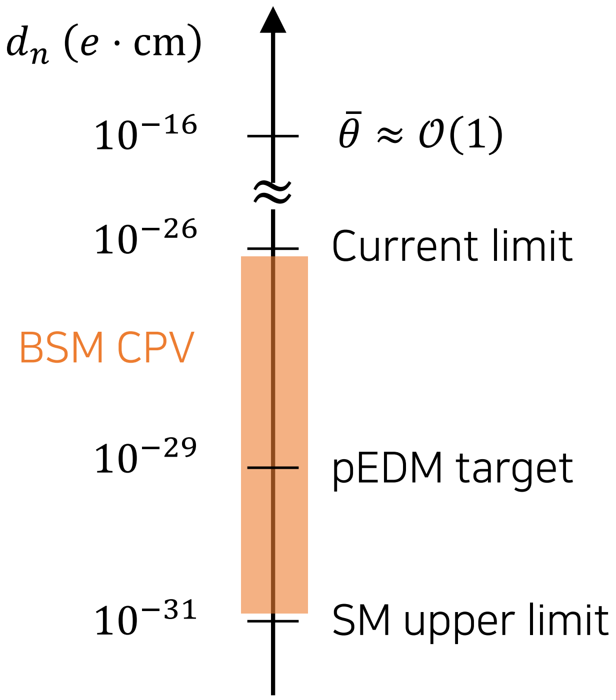
Seattle Snowmass Summer Meeting

Rare Processes and Precision Frontier: RF3 Discussions

Institute for Basic Science
ibs
기초과학연구원
CAPP
Center for Axion and Precision Physics Research

Physics reach of storage ring pEDM at $10^{-29}\ e \cdot \mathrm{cm}$

1. Competitive sensitivity to New Physics up to $1000\ \mathrm{TeV}$.
2. Three orders of magnitude improvement in θ_{QCD}.
3. Sensitive to certain Baryogenesis models: $\approx 10^{-28}\ e \cdot \mathrm{cm}$ in MSSM.
4. Best probe of Higgs CPV.
   - Two-loop Higgs coupling: $\tan \phi_{\mathrm{NP}} \approx \mathcal{O}(10^{-4})$.
   - x30 more sensitive than electrons with the same EDM.
5. Direct axion-like dark matter search.
   - Best experimental sensitivity at ultra-low frequency.
   - Also sensitive to dark energy or vector DM with a different experimental knob.



- First-ever "direct" measurement/constraint of d_p.
  - With 10^3 improvement from the best current d_n limit.
  - Complementary to atomic & molecular and optical (AMO) EDM experiments. E.g., complementary with the eEDM to sort out possible CPV sources.

Snowmass WP (many coauthors from the muon $g-2$ collaboration)

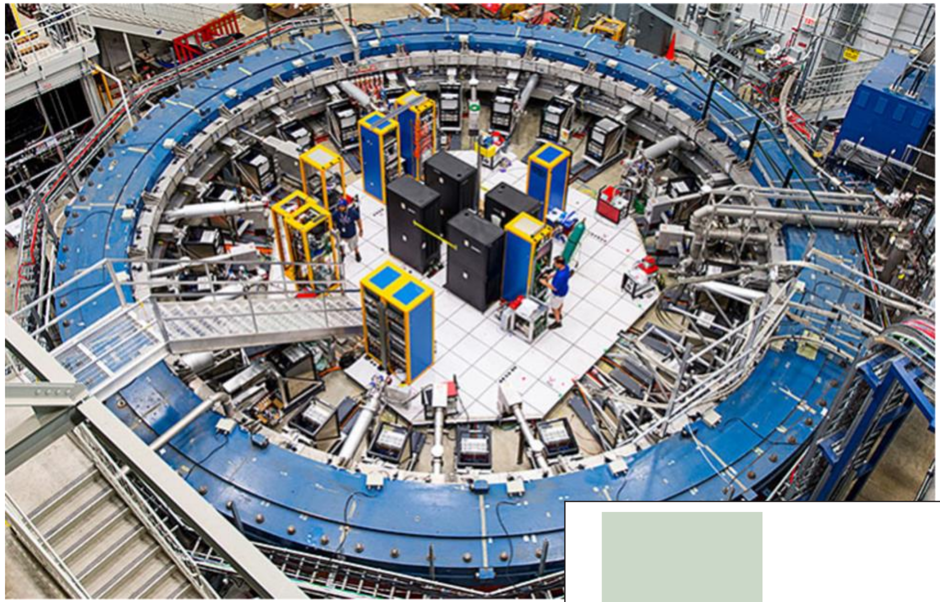
2205.00830

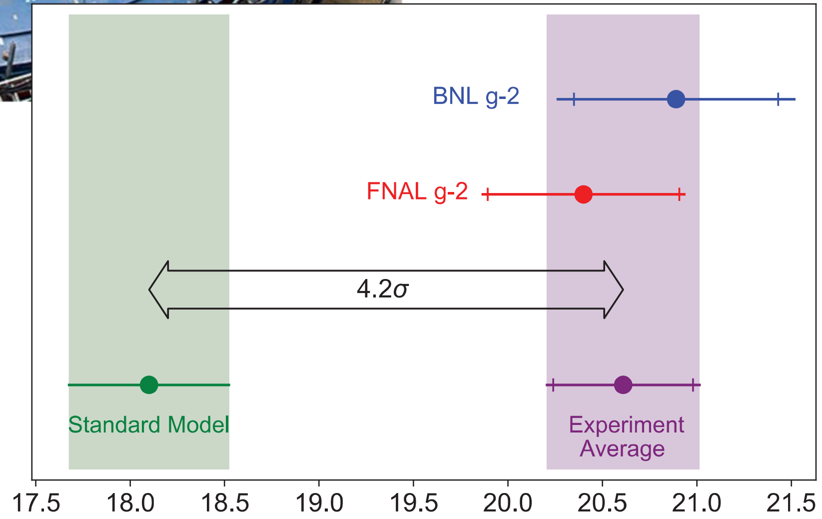
The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis[*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

Snowmass Cincinnati talk by Yannis Semertzidis
https://indico.fnal.gov/event/51844/contributions/240028/

- Muon $g-2$ first result in 2021.



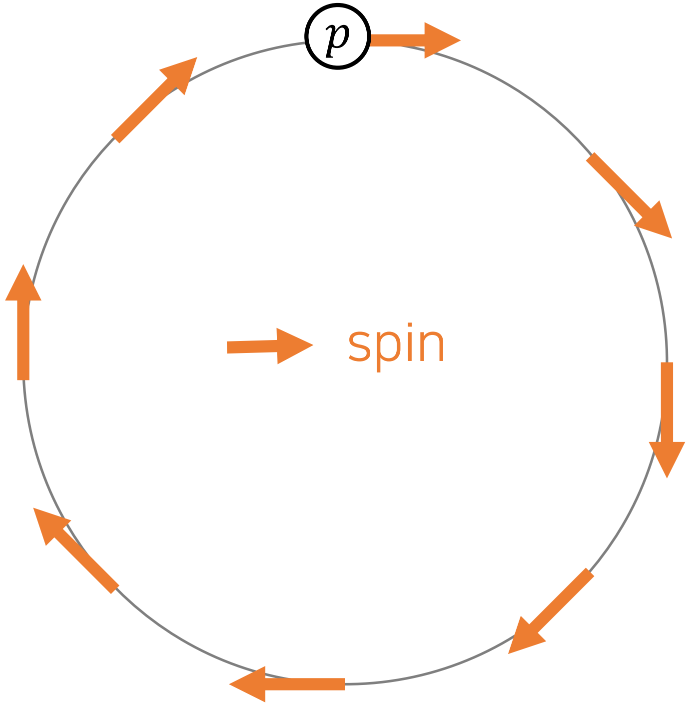


Storage ring pEDM in a nutshell

VOLUME 93, NUMBER 5 PHYSICAL REVIEW LETTERS week ending 30 JULY 2004

New Method of Measuring Electric Dipole Moments in Storage Rings

F. J. M. Farley,[7] K. Jungmann,[4] J. P. Miller,[2] W. M. Morse,[3] Y. F. Orlov,[5] B. L. Roberts,[2] Y. K. Semertzidis,[3] A. Silenko,[1] and E. J. Stephenson[6]



$$\boldsymbol{\omega}_a \approx -\frac{q}{m}\left[G\mathbf{B} - \left(G - \frac{m^2}{p^2}\right)\boldsymbol{\beta}\times\mathbf{E} + \frac{\eta}{2}(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B})\right]$$

Electric ring for the counter-rotating beams

$$\boldsymbol{\omega}_a \approx \cancel{\frac{q}{m}\left(G - \frac{m^2}{p^2}\right)}\boldsymbol{\beta}\times\mathbf{E} - \underbrace{\eta\frac{q}{2m}\mathbf{E}} \rightarrow \boldsymbol{\omega}_d$$

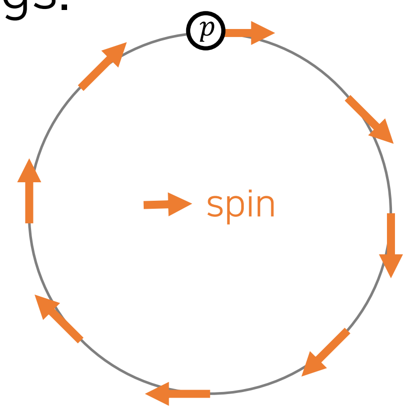
Magic momentum $p_m \equiv \frac{m}{\sqrt{G}}$

EDM precession: **vertical rotation** of the spin.

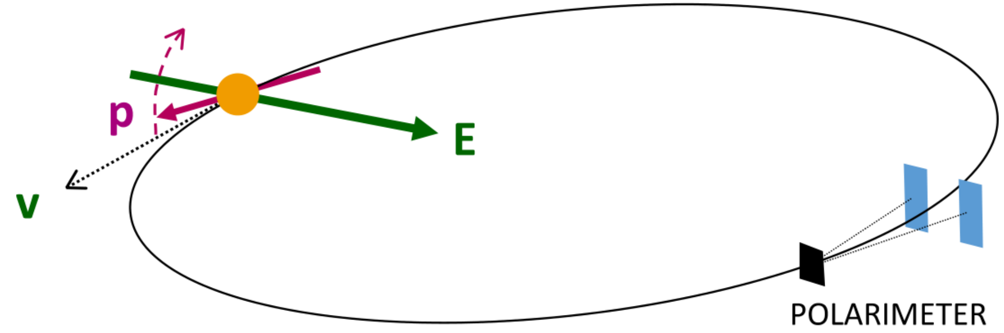
Storage ring pEDM in a nutshell

- Frozen-spin method: The most sensitive setup for probing the EDM in storage rings.
  - Spin is "frozen" with respect to the momentum.
  - Spin slowly precesses in vertical direction due to the EDM and radial $\mathbf{E}$.

$$\frac{\mathrm{d}\mathbf{s}}{\mathrm{d}t} = \mathbf{d} \times \mathbf{E}$$

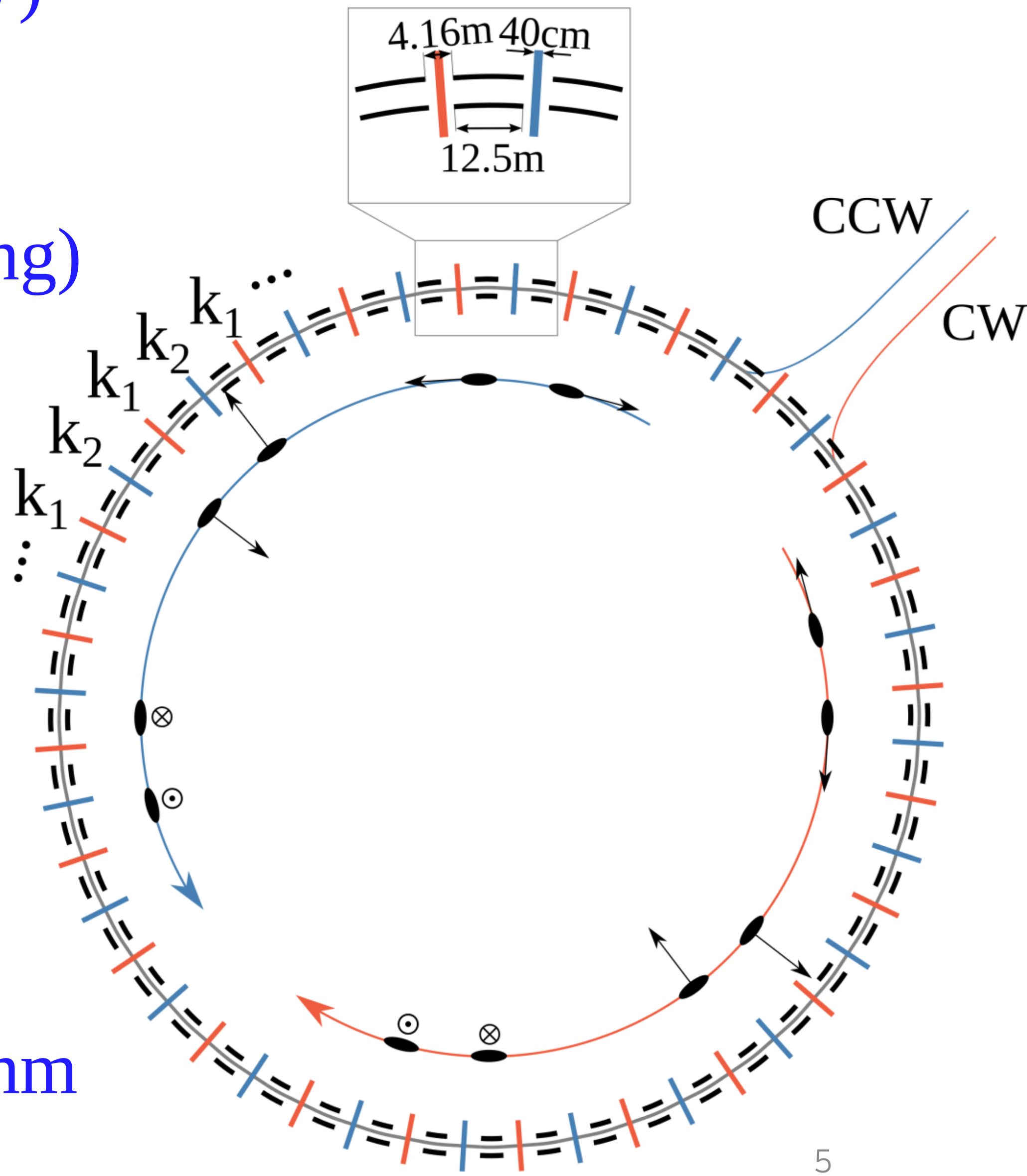


- Protons should be at the "magic" momentum $\approx 0.7\ \mathrm{GeV/c}$.
- Vertical polarization is measured by left-right asymmetry from the polarimeter.
  - $d_p = 10^{-29}\ e \cdot \mathrm{cm}$ corresponds to $1\ \mathrm{nrad}/s$ precession rate in the vertical polarization.
  - Takes one year of data accumulation with realistic parameters.
- It is an extremely high-intensity measurement.
  Understanding/controlling systematic uncertainties is everything.
  - Field errors, beam distribution, geometrical phases, closed-orbit planarity, ⋯.



Symmetries against systematic errors

- Clock-wise (CW) vs. Counter-Clock-Wise (CCW)
  - Eliminates vertical Electric field background
- Hybrid lattice (electric bending, magnetic focusing)
  - Shields against background magnetic fields
- Highly symmetric lattice (24 FODO systems)
  - Eliminates vertical velocity background
- Positive and negative helicity
  - Reduce polarimeter systematic errors
- Flat ring to 0.1 mm, beams overlap within 0.01 mm
  - Geometrical phases; High-order vertical E-field



Vertical velocity effect

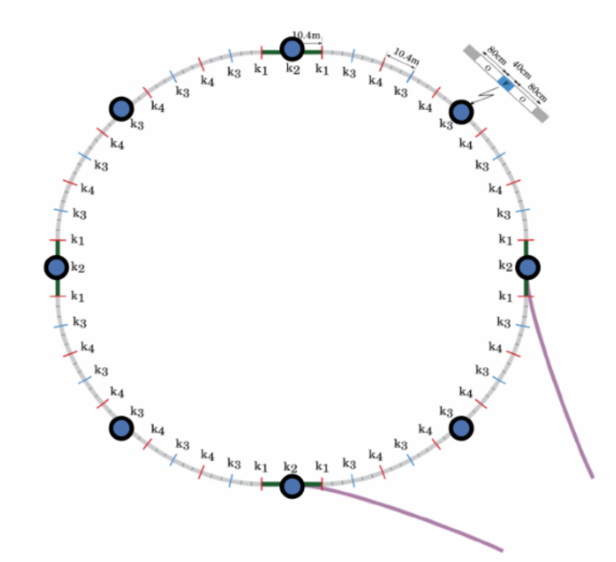
- Vertical velocity:

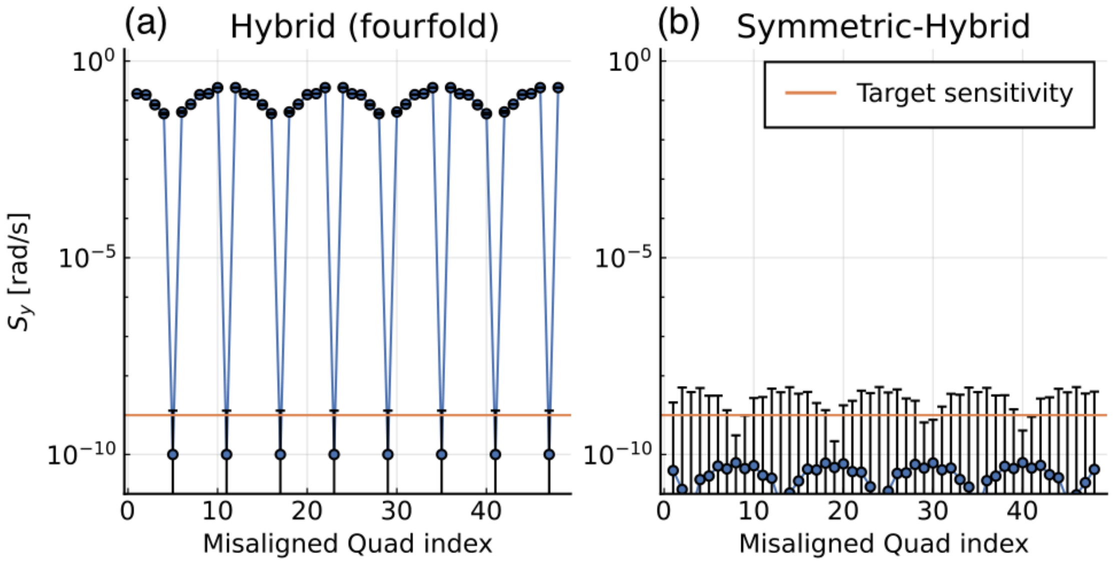
$$\dot{s}_y \propto \beta_y E_x s_x$$

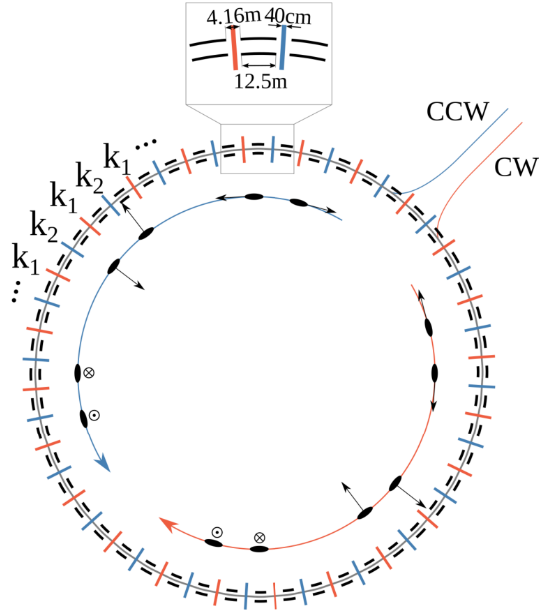
- Closed-orbit planarity (vertical alignment)

$$\langle \beta_y \rangle_{\text{bending}} \neq 0$$

- The radial polarization ($s_x = 1$) maximizes the effect. Symmetry is a key to suppressing it! Vertically misalign one quadrupole at a time by $100\ \mu\text{m}$.







Combined systematic effects

- Symmetric-hybrid + CR beam does it all.

$$\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{EDM}} = \frac{1}{2}\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{CW1,2}} - \frac{1}{2}\left(\frac{\mathrm{d}S_y}{\mathrm{d}t}\right)_{\mathrm{CCW1,2}}$$

All systematic effects combined. Filtering out false EDM. Misalignment and the beam separation.

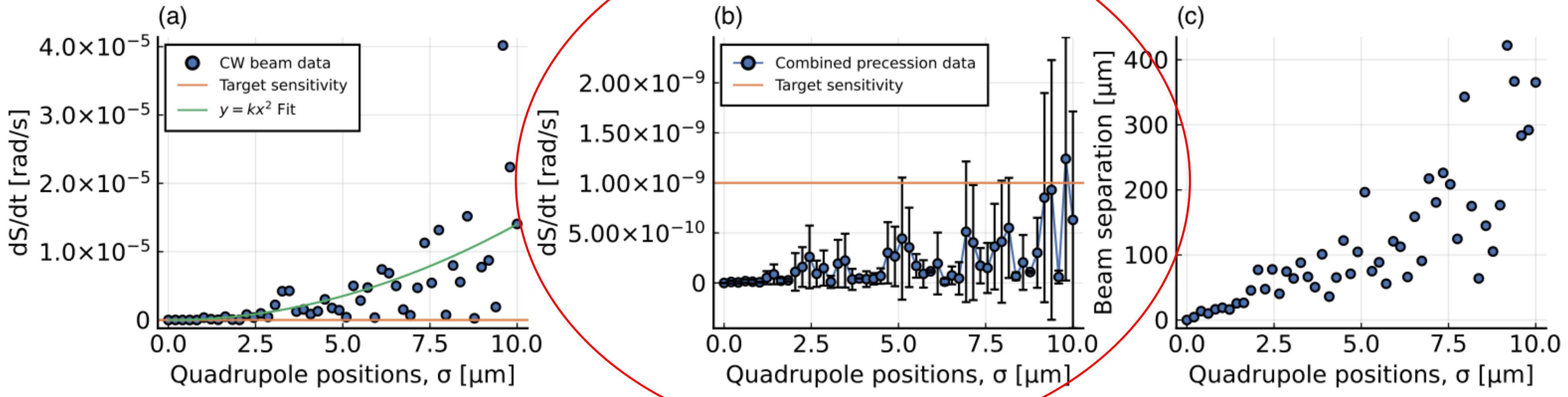


FIG. 9. (a) *Longitudinal polarization case, CW beam only*. Vertical spin precession rate (absolute) vs random misalignments of quadrupoles in both x, y directions by rms σ with different seeds per each point (when the same seeds are used everywhere, the $y = kx^2$ fit is perfect, meaning that every point can be extrapolated to any rms σ value using this functional form). Combination with CCW and quadrupole polarity switching achieves large cancellation—see part (b). (b) *CW and CCW beam and with quadrupole polarity switching*. Total combination as presented in Appendix C. Notably, the background vertical spin precession rate (absolute) stays below the target sensitivity. Irregularity of the points is discussed in Appendix B. (c) Correspondence between CR beam separation and rms σ quadrupole misalignments.

Storage ring probes of DM/DE

- Couplings with dark matter (DM) and dark energy (DE)

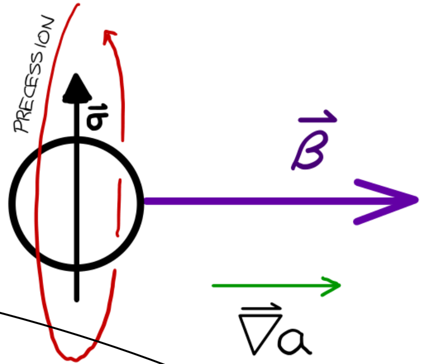
P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

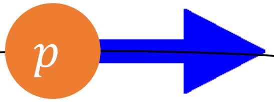
  - ALP or vector DM wind ($g_{aNN}\nabla a \cdot \hat{\sigma}_N$) ⇒ anomalous longitudinal oscillating B field.
  - DE wind ⇒ anomalous longitudinal B field.

The storage ring is optimal since $\beta \approx 0.6$ is large!

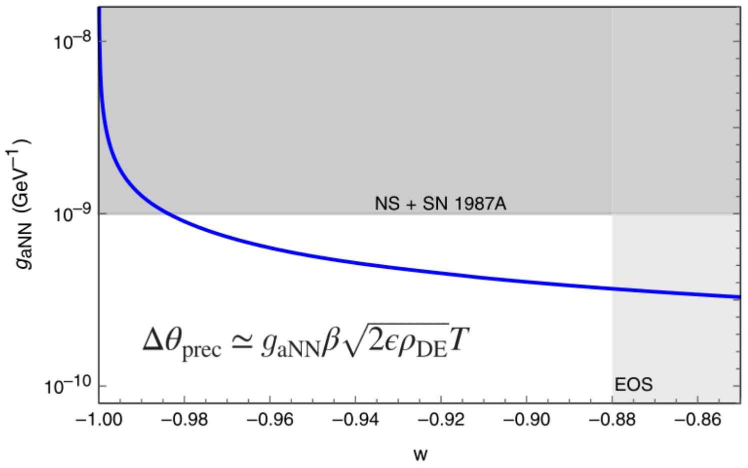
  - Radial initial polarization is assumed.

$$\boldsymbol{\omega}_{\mathbf{DM}} \propto \cos(m_a t)\,\hat{\beta}$$
$$\boldsymbol{\omega}_{\mathbf{DE}} \propto \hat{\beta}$$

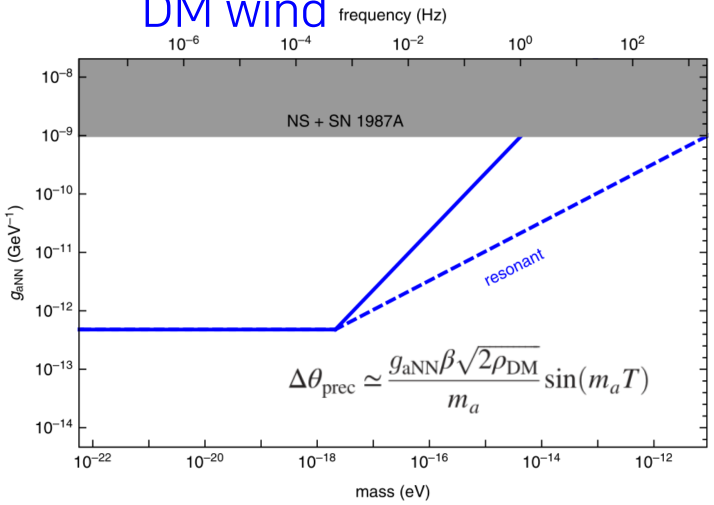




DE wind



DM wind



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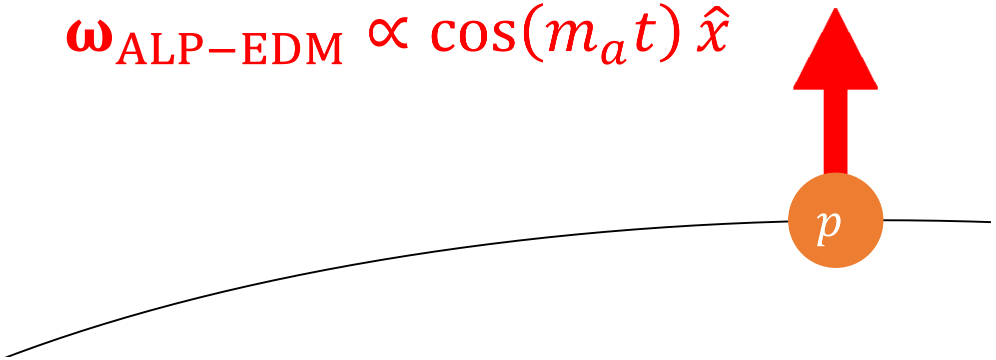
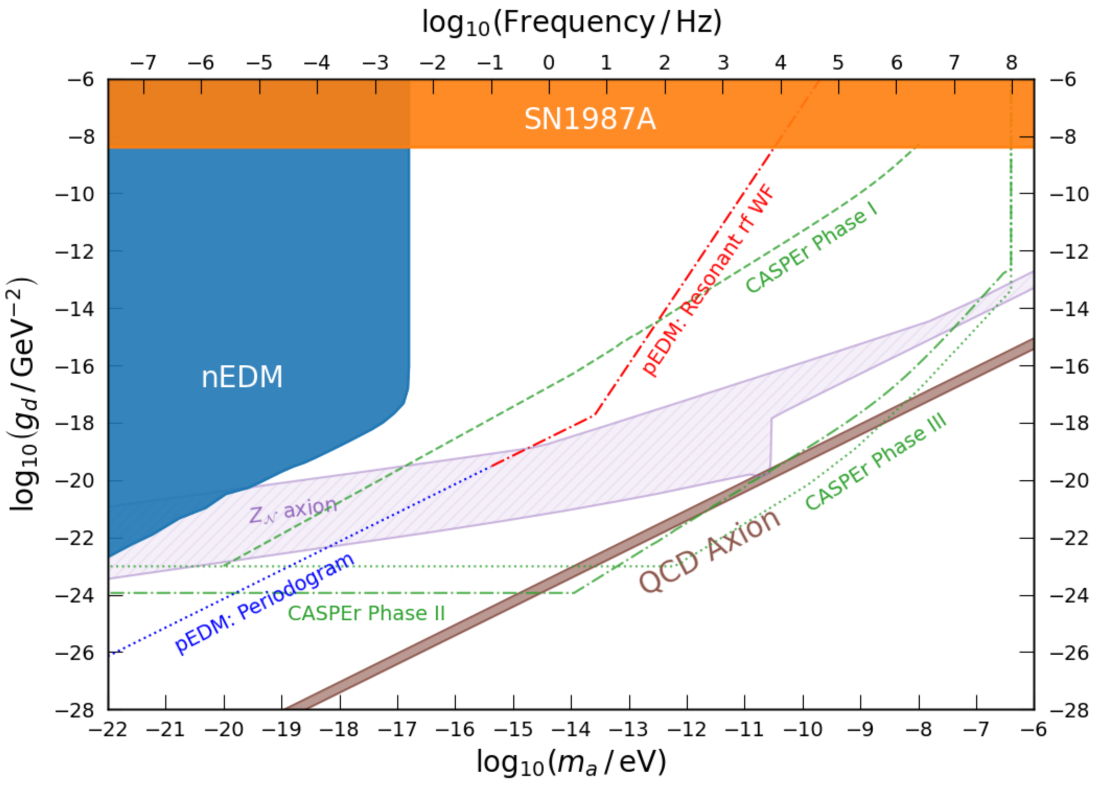
  P. Graham et al., PRD **103**, 055010 (2021)

  - ALP-EDM ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) ⇒ oscillating EDM at m_a. For the QCD axion: $d_N^{\rm QCD} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.

$\boldsymbol{\omega}_{\mathbf{ALP-EDM}} \propto \cos(m_a t)\,\hat{x}$



ALP-EDM coupling



- Storage ring probes of axion-induced oscillating EDM.
  S. Chang *et al.*, PRD **99**, 083002 (2019).
- Complementary method using an rf Wien filter.
  On Kim and Y. Semertzidis, PRD **104**, 096006 (2021)
- Parasitic measurement with pEDM experiment.
  - Low frequency: Periodogram analysis. The best sensitivity!
  - High frequency: Resonant rf Wien filter.

Putting together the pEDM ring: No new development needed

System	Risk factor, comments
Ring construction, beam storage, stability, IBS	Low. Strong (alternate) focusing, a ring prototype has been built (AGS analog at BNL) in 60's. Lattice elements placement specs are ordinary. Intra-beam-scattering (IBS) OK below transition.
E-field strength	Low. Plate-units are similar to those ran at Tevatron with higher specs.
E-field plates shape	Medium. Make as flat as conveniently possible. Probe and shim out high order fields by intentionally splitting the CR-beams
Spin coherence time	Low. Ordinary sextupoles will provide $>10^3$s.
Beam position monitors (BPM), SQUID-based BPMs.	Medium. Ordinary BPMs and hydrostatic level system (HLS) to level the ring to better than 0.1mm; SQUID-based or more conventional BPMs to check CR-beams split to 0.01mm.
High-precision, efficient software	Low. Cross-checking our results routinely
Polarimeter	Low. Mature technology available

Last P5 identified this experiment as an R&D project we completed two years ago.

References

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14. G.W. Bennett *et al.*, An improved limit on the muon electric dipole moment, Phys. Rev. D 80, 052008 (2009)
15. F.J.M. Farley *et al.*, A new method of measuring electric dipole moments in storage rings, Phys. Rev. Lett. 93, 052001 (2004)
16. …

What we want from Snowmass

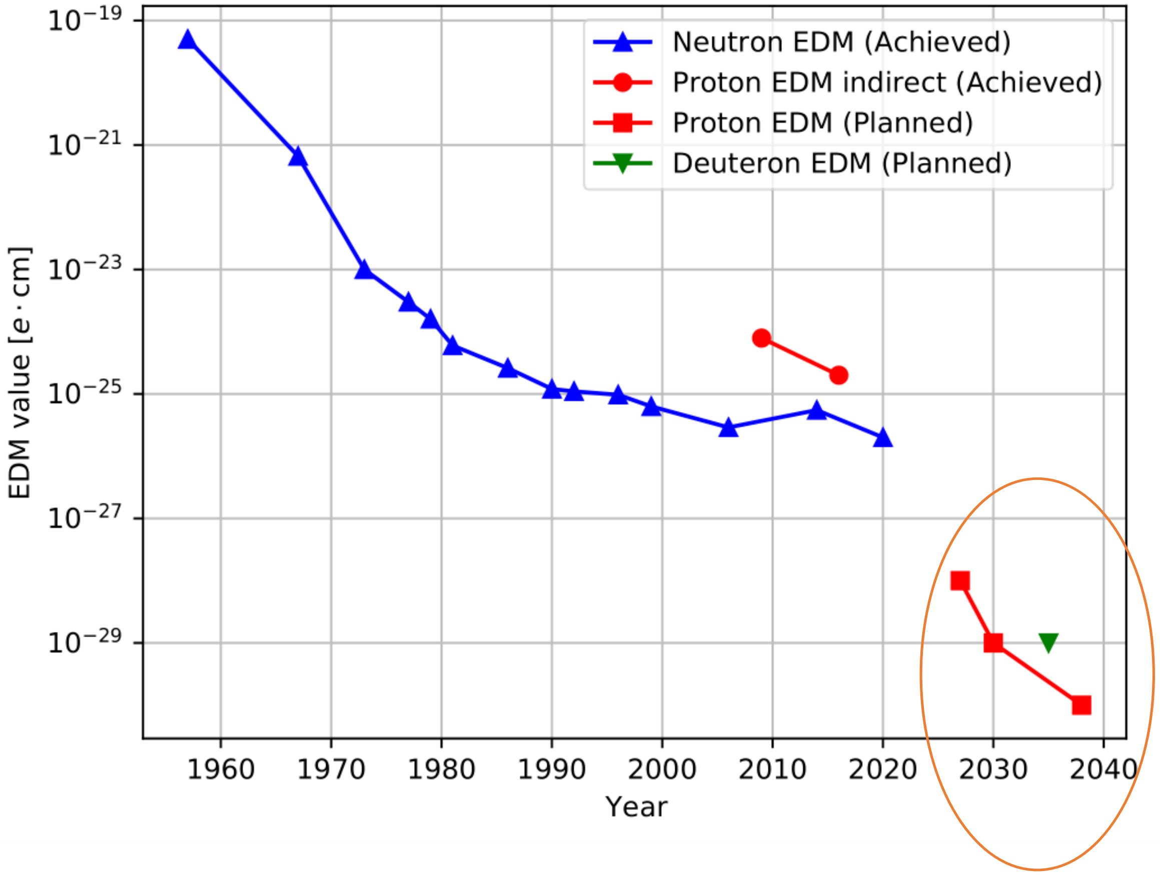
- Strong endorsement of our physics.
    1. New physics up to $1000\ \mathrm{TeV}$.
    2. Three orders of magnitude improvement in θ_{QCD}.
    3. Probe of specific baryogenesis models.
    4. Best probe of Higgs CPV.
    5. Direct axion-like dark matter search.

- Identification of the storage ring proton EDM experiment as a core consensus in the Frontier.

Summary and Outlook

- Storage ring proton EDM at $10^{-29}\ e \cdot \mathrm{cm}$ within the decade (BNL/AGS option). Great physics reach.
- No need to develop new technologies. The cost of the experiment similar in scale to the muon g-2.
- Comprehensive systematic error studies with realistic experimental parameters were conducted. The R&D phase for the pEDM ring has been completed. PRD **105**, 032001 (2022)
- After protons, a natural extension is to have deuterons, ^{3}He, and other particles with the inclusion of magnetic fields (further work required).

Technically driven schedule



Backups

Storage ring EDM

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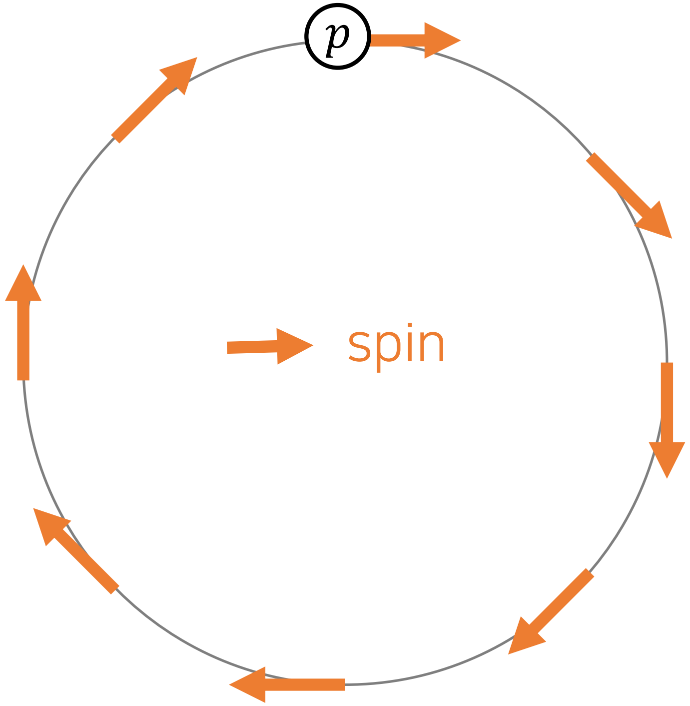
- Frozen-spin is the most sensitive setup for probing the EDM in storage rings.



$$\boldsymbol{\omega}_a \approx -\frac{q}{m}\left[G\mathbf{B} - \left(G - \frac{m^2}{p^2}\right)\boldsymbol{\beta}\times\mathbf{E} + \frac{\eta}{2}(\mathbf{E} + \boldsymbol{\beta}\times\mathbf{B})\right]$$

Electric ring for the counter-rotating beams

$$\boldsymbol{\omega}_a \approx \cancel{\frac{q}{m}\left(G - \frac{m^2}{p^2}\right)}\boldsymbol{\beta}\times\mathbf{E} - \underbrace{\eta\frac{q}{2m}\mathbf{E}} \rightarrow \boldsymbol{\omega}_d$$

Magic momentum $p_m \equiv \frac{m}{\sqrt{G}}$

EDM precession : vertical rotation of the spin.

Storage ring EDM

Emphasize systematics

- Proton "magic" values PRD **105**, 032001 (2022):

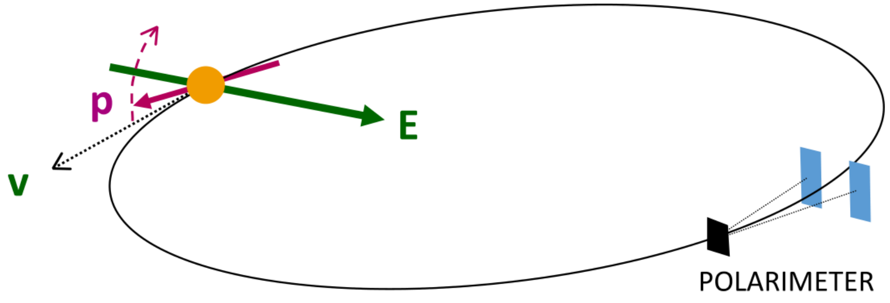
G	β	γ	p	KE
1.793	0.598	1.248	0.7 GeV/c	233 MeV

- EDM precession:

$$\omega_d = \frac{d}{s}E \approx 1\ \mathrm{nrad/s}\left(\frac{d}{10^{-29}\ e\cdot\mathrm{cm}}\right)\left(\frac{1/2}{s}\right)\left(\frac{E}{3.3\ \mathrm{MV/m}}\right)$$

- Statistical uncertainty PRD **104**, 096006 (2021):

$$\sigma_{\omega_d} = \frac{2.3}{PA\sqrt{N_{\mathrm{cyc}} f \tau_p T_{\mathrm{tot}}}} \approx 1\ \mathrm{nrad/s}\left(\frac{0.8}{P}\right)\left(\frac{0.6}{A}\right)\sqrt{\left(\frac{4\times10^{10}}{N_{\mathrm{cyc}}}\right)\left(\frac{1\%}{f}\right)\left(\frac{2\times10^{3}\ \mathrm{s}}{\tau_p}\right)\left(\frac{1\ \mathrm{year}}{T_{\mathrm{tot}}}\right)}$$



P : Initial polarization.
A : Analyzing power (coefficient for LR asymmetry from polarimeter).
N_{cyc} : Number of stored particles per cycle.
f : Detector efficiency.
τ_p : Spin coherence time (SCT).
T_{tot} : Total measurement time.

Storage Ring Electric Dipole Moments exp. options

Fields	Example	EDM signal term	Comments
Dipole magnetic field (B) (Parasitic)	Muon g-2	Tilt of the spin precession plane. (Limited statistical sensitivity due to spin precession)	Eventually limited by geometrical alignment. Requires consecutive CW and CCW injection to eliminate systematic errors
Combination of electric & and magnetic fields (E, B) (Combined lattice)	Deuteron, ^{3}He, proton, muon, etc.	Mainly: $\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$	High statistical sensitivity. Requires consecutive CW and CCW injection with main fields flipping sign to eliminate systematic errors
Radial Electric field (E) & Electric focusing (E) (All electric lattice)	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. Requires demonstration of adequate sensitivity to radial B-field syst. error
Radial Electric field (E) & Magnetic focusing (B) (Hybrid, symmetric lattice)	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. Only lattice to achieve direct cancellation of main systematic error sources (its own "co-magnetometer"). GOLD STANDARD!

Effect as a function of azimuthal harmonic N

COMPREHENSIVE SYMMETRIC-HYBRID RING DESIGN FOR A … PHYS. REV. D **105**, 032001 (2022)

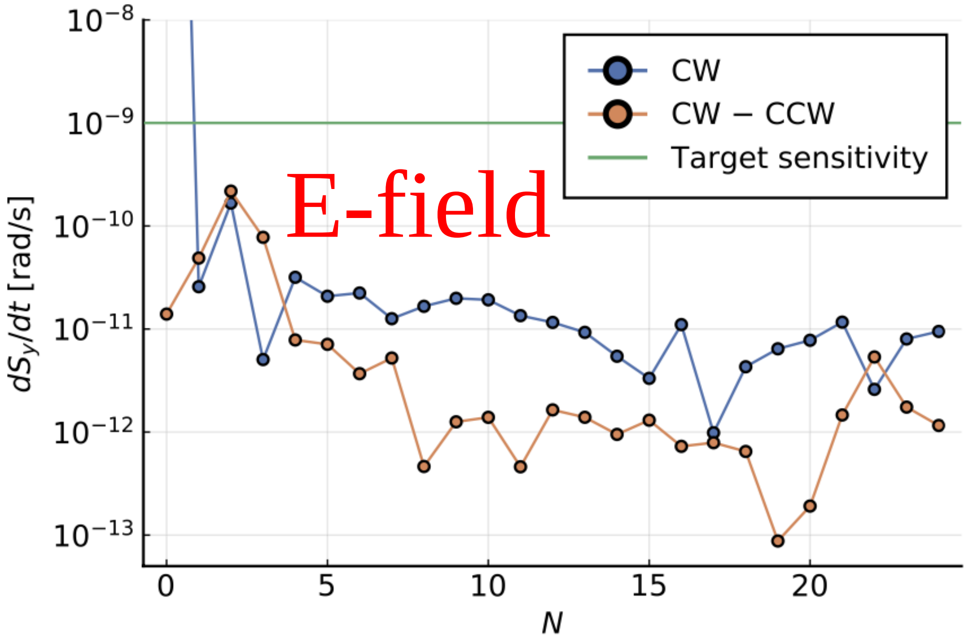


FIG. 7. *Longitudinal polarization case* $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is below the target sensitivity for all N. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

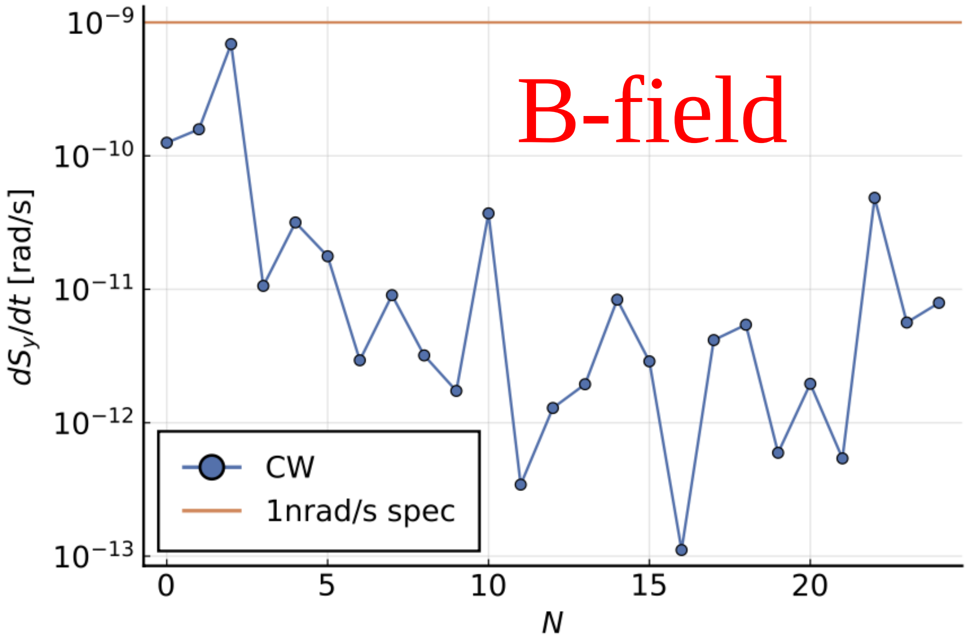


FIG. 8. *Longitudinal polarization case* $S_s = 1$, *CW beam only.* Vertical spin precession rate vs $B_x = 1$ nT field N harmonic around the ring azimuth. The magnetic field amplitude is chosen to be similar to beam separation requirements in Sec. IV A, and more than $B_x = 1$ nT splits the CR beams too much. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

Storage ring probes of DM/DE

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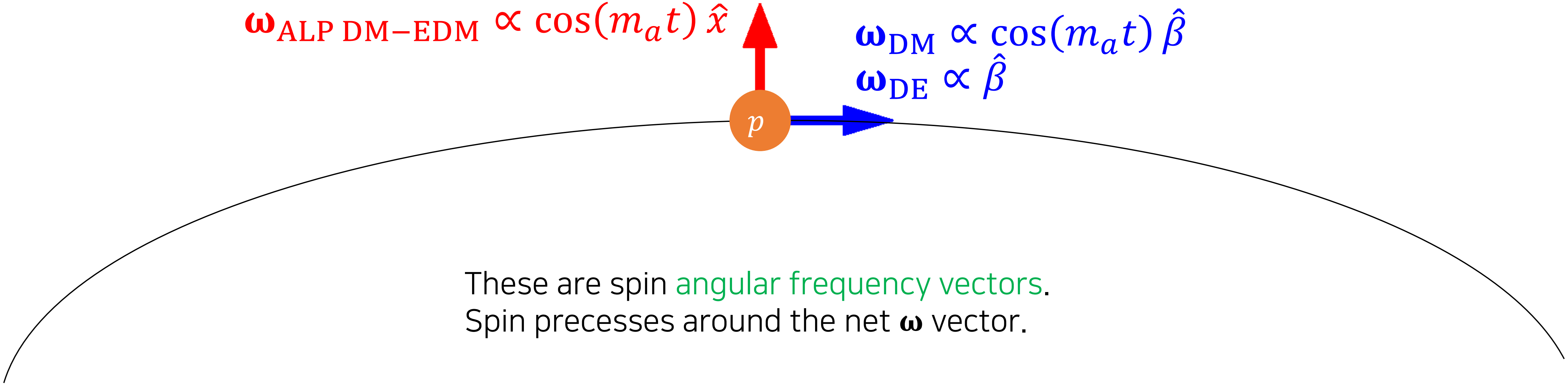
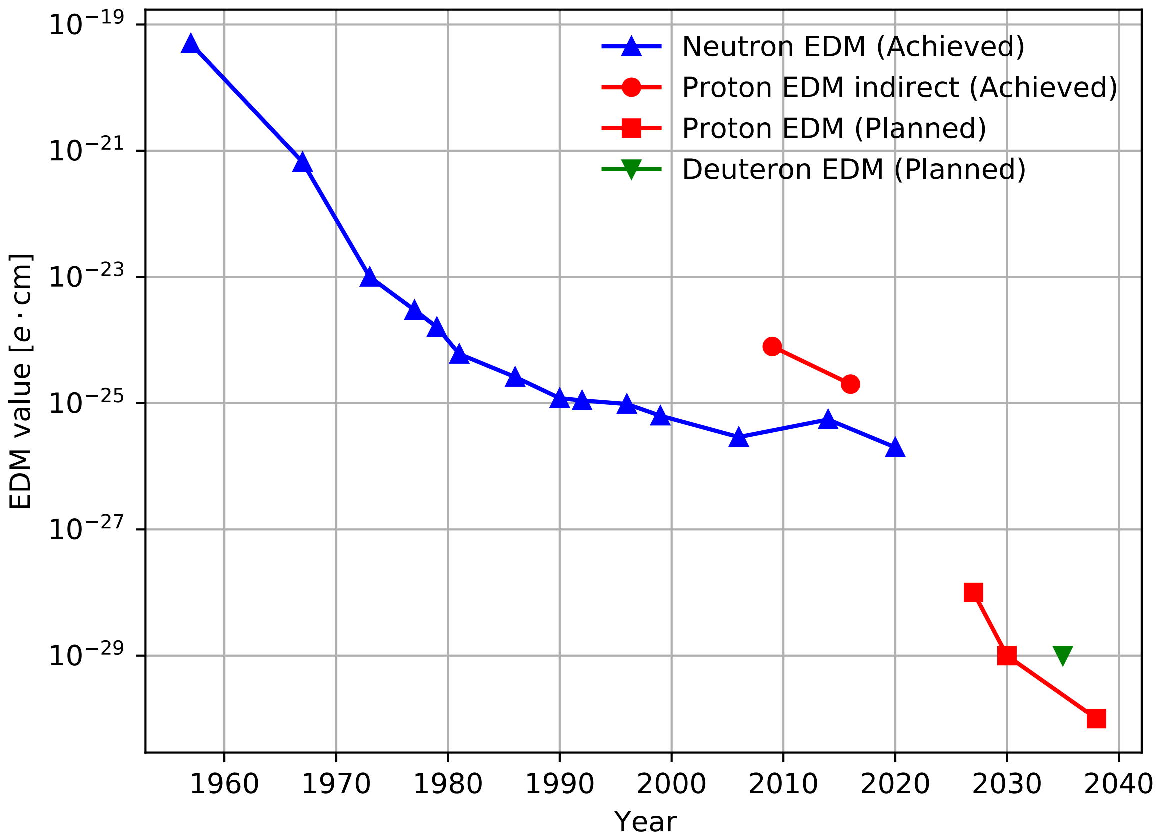
  - ALP or vector DM wind ($g_{aNN} \nabla a \cdot \hat{\sigma}_N$) $\Rightarrow$ anomalous longitudinal oscillating B field.
  - DE wind $\Rightarrow$ anomalous longitudinal B field.

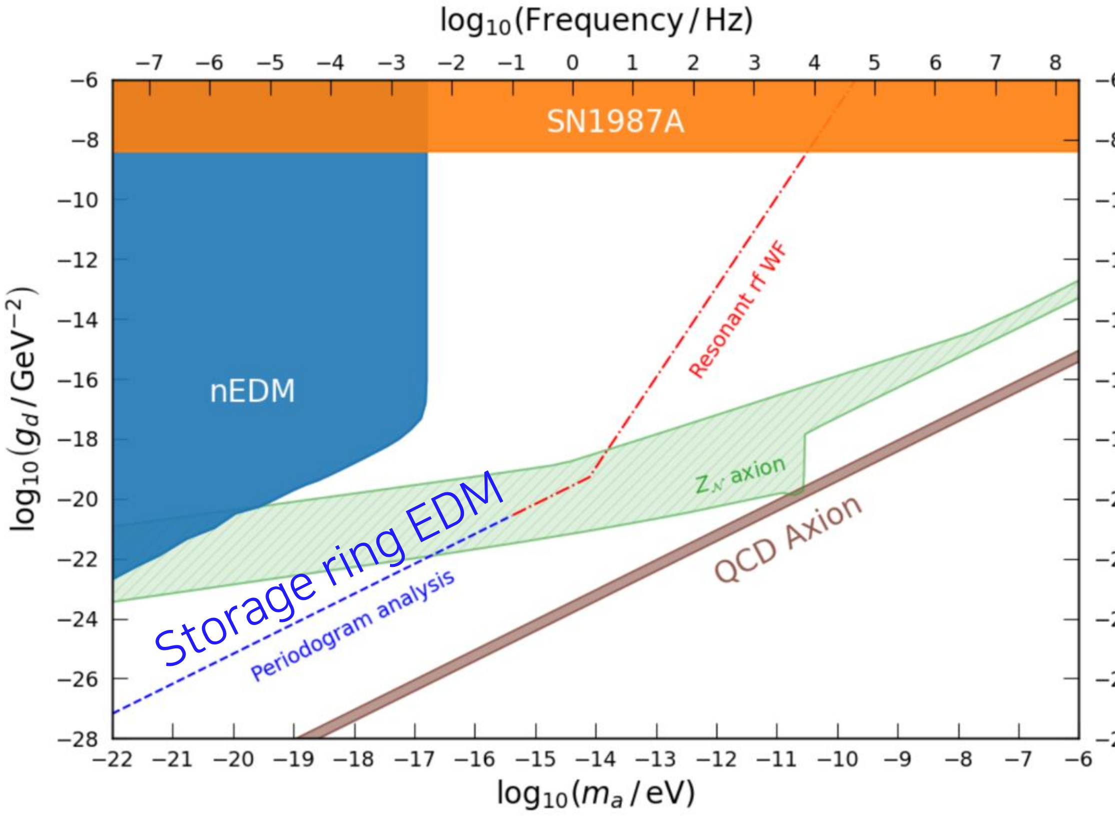


These are spin angular frequency vectors.
Spin precesses around the net $\boldsymbol{\omega}$ vector.

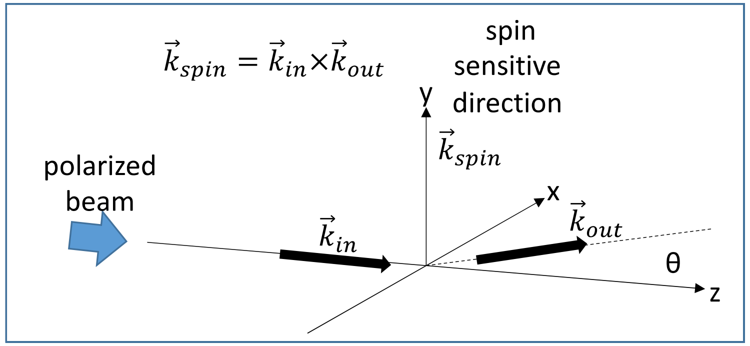
Storage ring proton EDM at 10^{-29} e-cm: Timeline, physics reach

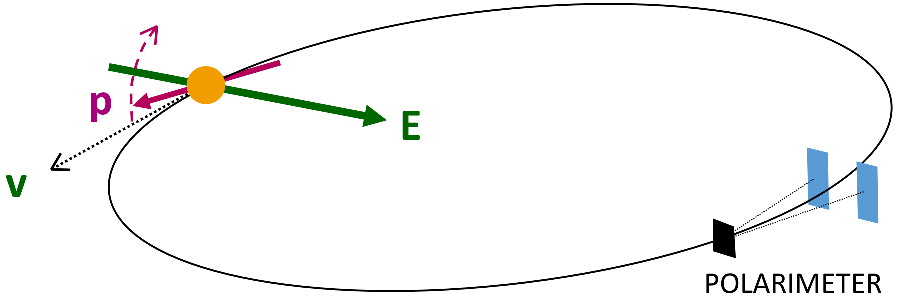
- In progress or still ahead: Snowmass, CDR, proposal/TDR, ring construction, injection, storage.
- Experience with muon g-2 experiment; possible to have interesting results within the decade.
- Competitive EDM sensitivity:
  - New-Physics reach at 10^3 TeV.
  - Best probe on Higgs CPV, Marciano: proton is better than H→ $\gamma\gamma$, and 30x more sensitive than electron with same EDM.
  - Three orders of magnitude improvement in θ_{QCD} sensitivity.
  - Direct axion dark matter reach (best exp. sensitivity at very low frequencies).





Snowmass paper on pEDM





Frozen spin method:

- Spin aligned with the momentum vector
- Radial E-field precesses EDM/spin vertically
- Monitoring the spin using a polarimeter

arXiv:2205.00830v1 [hep-ph] 25 Apr 2022

The storage ring proton EDM experiment

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Large Surface Area Electrodes

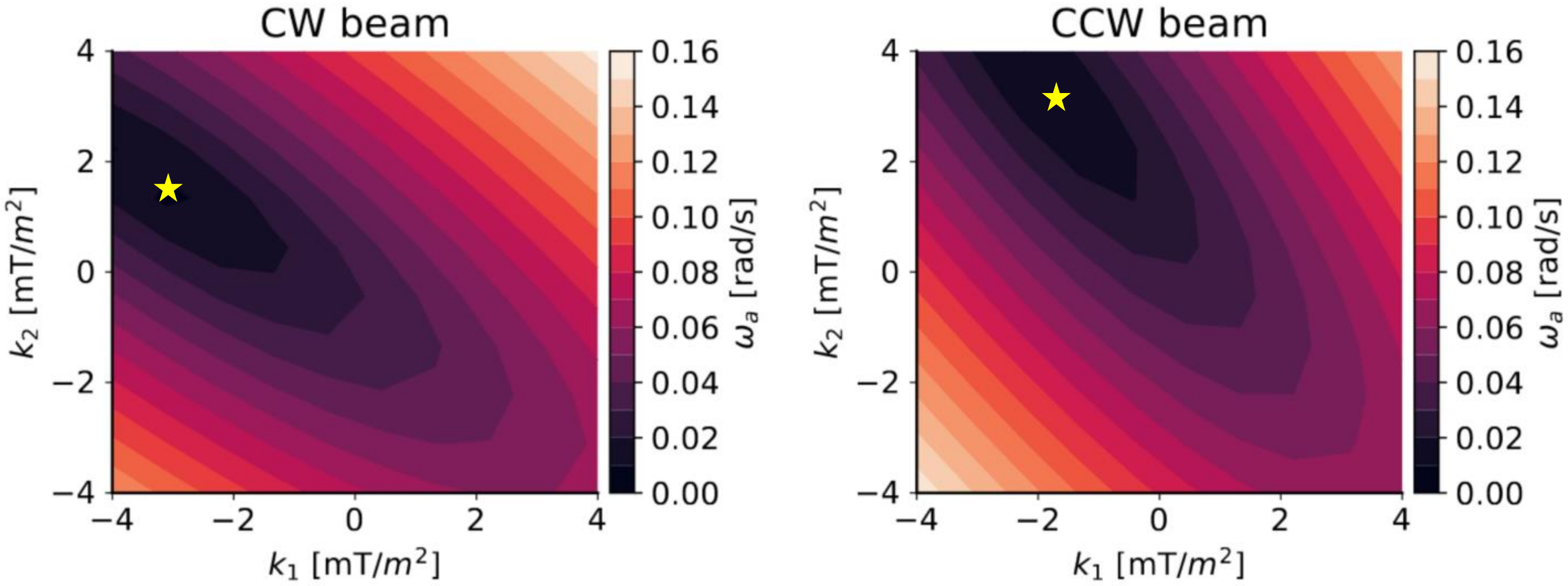
Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM (low risk)
Length/unit	2.6m	4.5m	5×2.5m
Gap, E-field	5cm, 7.2 MV/m	10cm, 4 MV/m	4cm, 4.5 MV/m
Height	0.2m	0.4m	0.2m
Number	24	2	48
Max. HV	±(150-180)KV	±200KV	±90KV

Spin coherence time

- Time that the polarization remain coherent (polarization lifetime): $P = P_0 e^{-t/\tau_p}$.
- Sensitivity $\sigma_d \propto \tau_p^{-1/2}$: the longer τ_p, the better.
- Dominant source of decoherence: momentum dispersion → tune shift (ΔQ or $\Delta\omega_a$).
- Sextuple fields can manipulate chromaticity: $\Delta Q/\Delta p$.

$$B_x = 2k^m xy, \qquad B_y = k^m(x^2 - y^2)$$

- Alternating sextuple fields ($k_1^m, k_2^m, k_1^m, k_2^m \cdots$) are known to be better to optimize the chromaticity.

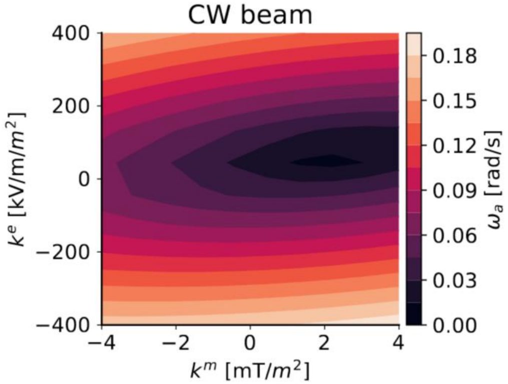


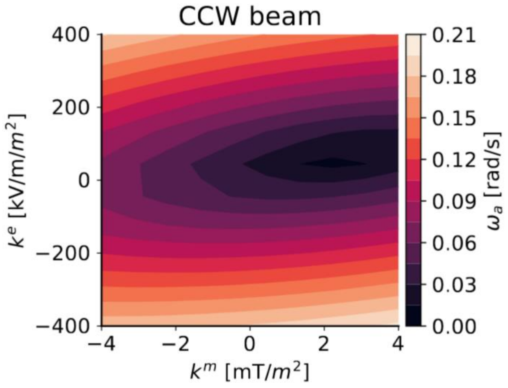
Spin coherence time

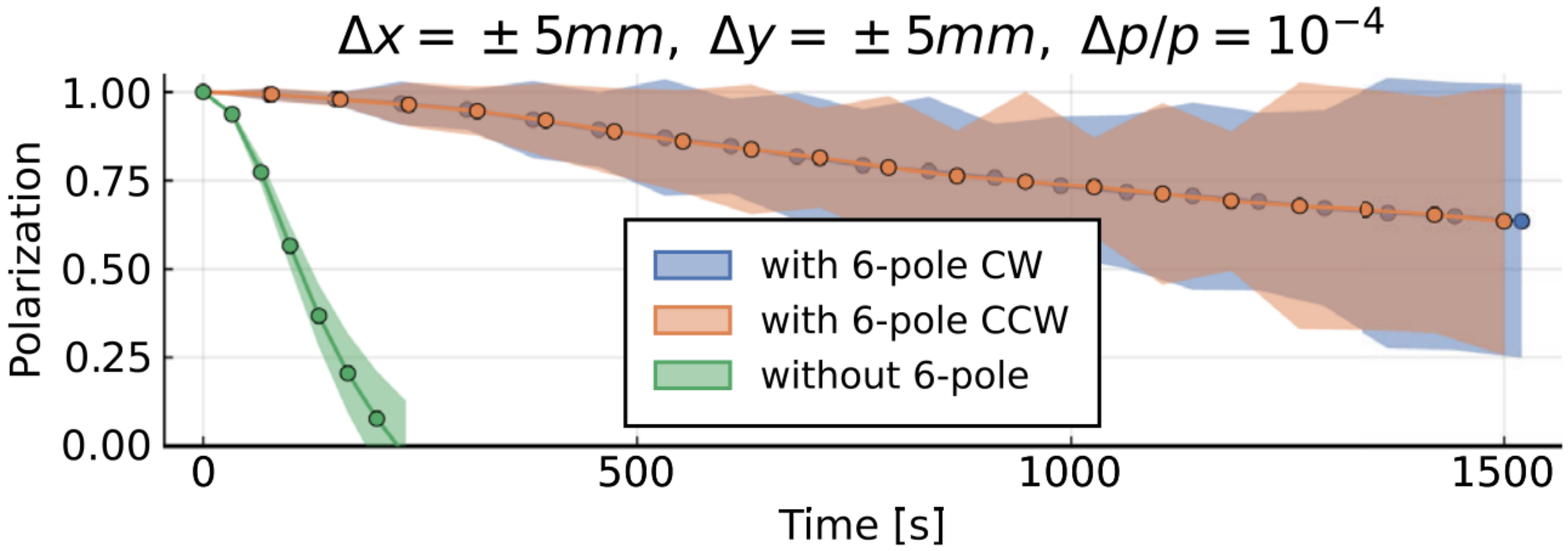
- Electric sextuples are exploited at the same time ⇒ Hybrid sextuples.
- Zhanibek's relations for optimal SCT.

$$k_1^m = -k_2^m, \qquad k_1^e = k_2^e$$

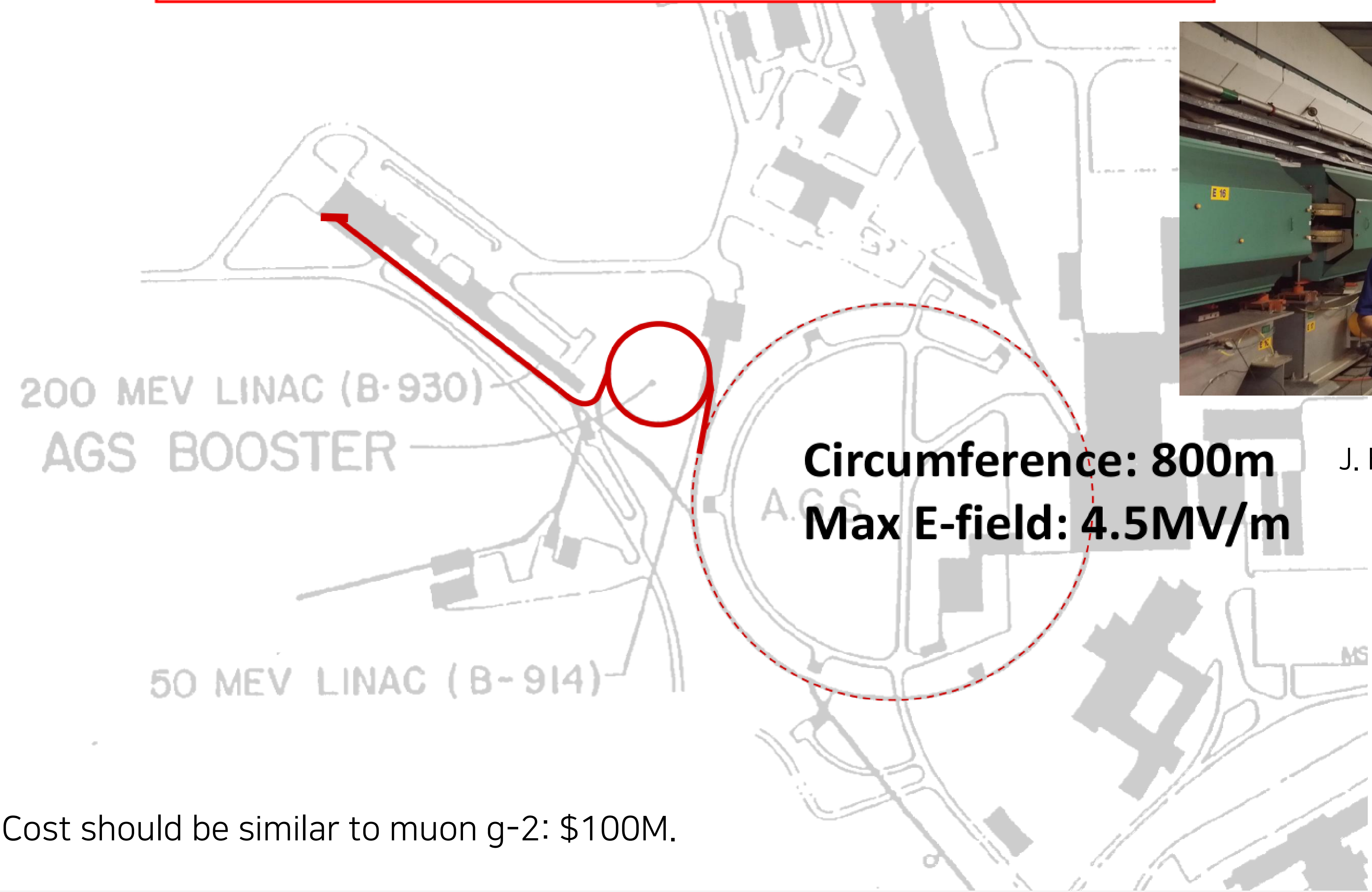
- Effect became symmetric for CW and CCW.







Possibility: **The proton EDM in the AGS tunnel at BNL**

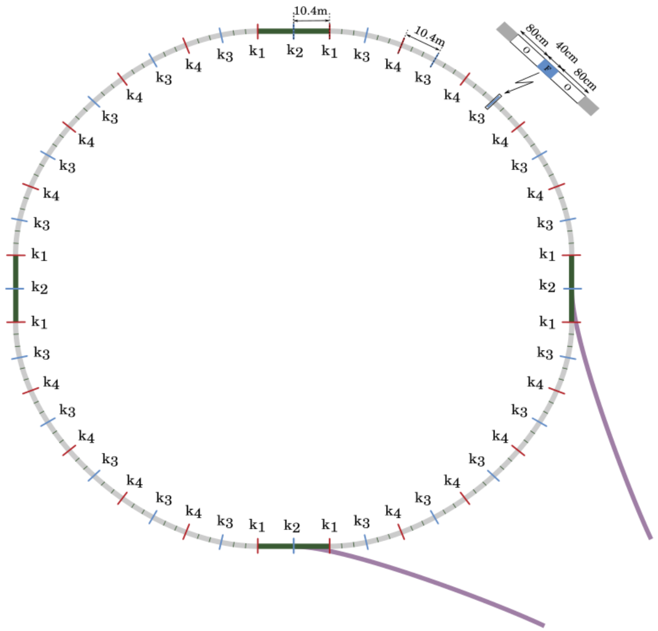


AGS tunnel
J. Benante and W. Morse

Cost should be similar to muon g-2: $100M.

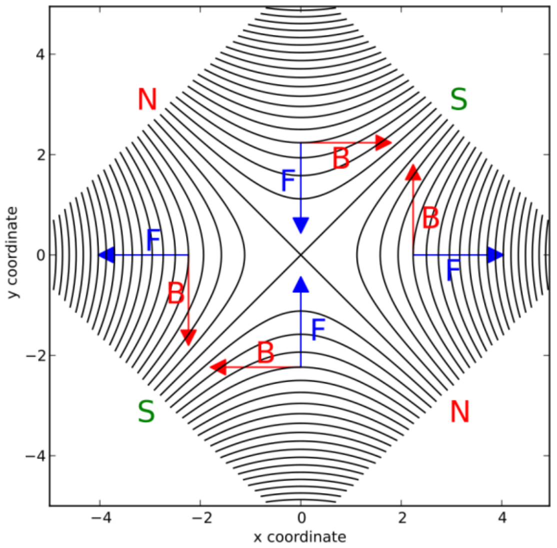
Breakthroughs

All-electric ring (4-fold)	Hybrid ring	Symmetric-hybrid ring



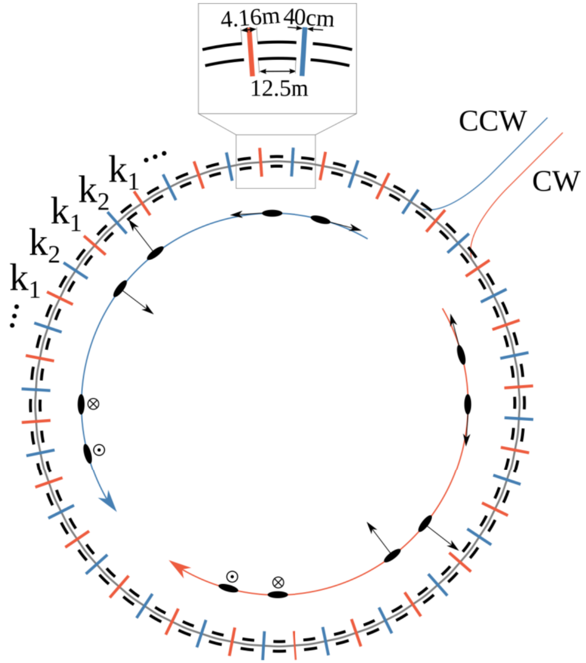
- Original design.
- Counter-rotating beams can reveal the false EDM signal from vertical E effect.

RSI **87**, 115116 (2016)



- Replacing electric focusing with magnetic focusing washes out radial B effect.

PRAB **22**, 034001 (2019)



- Symmetric lattice washes out the vertical velocity effect (closed-orbit planarity).
- Most comprehensive and beneficial design with practical parameters.

PRD **105**, 032001 (2022)

Systematic effects

- Main systematic effects and corresponding remedies.

Name	T-BMT term	Spec. w/o remedy	Remedy
Radial B	$s_s \cdot B_x$	$B_x \lesssim \mathcal{O}(10\ \mathrm{aT})$	Magnetic focusing
Vertical E	$s_s \cdot E_y$	$E_y \lesssim \mathcal{O}(1\ \mathrm{nV/m})$	Counter-rotating beams
Vertical velocity	$s_x \cdot \beta_y \cdot E_x$	$\Delta y_{\mathrm{misalign}} \lesssim \mathcal{O}(1\ \mathrm{nm})$	Symmetric ring PRD 105, 032001 (2022)

- Other systematic errors are also under control.
  - Geometrical phases and higher-order E_y fields: Spin-based alignment (SBA), closed-orbit planarity $100\ \mu\mathrm{m}$, CR beam separation $10\ \mu\mathrm{m}$.
  - Polarimeter systematics errors N. Brantjes et al., NIM A664, 49 (2012): Positive and negative helicity.